ENGINEERING CASE LIBRARY

ECL 195A

RESEARCH ON HYBRID AC/DC ELECTRIC POWER SYSTEMS AND SYSTEM STABILITY TECHNIQUES

Part A

Research and Tests on AC/DC System Operation

When we began to study the use of DC, very little was known. There were no good textbooks. We searched for as much information as we could find, and finally bought four years of back copies of an English magazine which dealt with DC and started reading from scratch.

-John J. Dougherty
Philadelphia Electric
Company

Written by C. E. Prince, Jr. with the support of the Middle Atlantic Power Research Committee. Published by the Engineering Case Program with support from the National Science Foundation.

INTRODUCTION

Research is a human activity intended to uncover new knowledge. This case history describes an engineering research project which has provided much new knowledge on the operation of an electric power system in which some lines are carrying DC rather than conventional AC.

Spanning a period of over six years, from 1963 to 1970, the project was managed by one electrical engineer, assisted by a team of about five other engineers from American electric utilities--the team's members, except for the manager, changed every year. A model, involving one DC line and two AC lines as parallel ties between two AC systems, was built and experiments performed. A computer simulation was written. While experimenting with the model, the research group made an important observation--that certain troubles, or faults, on the main AC parts of the system, faults which could normally lead to system instability, can be compensated for quickly and effectively by instantaneously varying in a proper way the power being carried over the DC parts of the system.

As U. S. electric power systems grow larger and more interdependent, carry more power, and involve greater machines, the possibility of system instability causes more concern among system engineers. Perhaps judicious use of DC can contribute to achieving more stable, reliable systems.

A NEW RESEARCH PROJECT

John J. Dougherty, electrical engineer with the Philadelphia Electric Company, Philadelphia, Pennsylvania, found himself appointed project manager of a new and major research project in September, 1963. It was a large effort, the Edison Electric Institute's Research Project 56 on AC/DC System Operation. Special contributions from 42 EEI member companies, investor-owned electric utilities from all parts of the United States, funded the project. For analytical studies $200,000 was allocated, and $2,000,000 was set aside for building and testing a small-scale physical model (700KW) of an entire electric power system--generators, transmission lines, motors, and other loads--to use not only normal three-phase AC but, especially, to include a rectifier (AC→DC) - DC transmission line - inverter (DC→AC) link to operate in parallel with two AC transmission lines.

An over-all supervisory group or "task force," under whom John was to work and to whom he would report, discussed the purpose of the program in 1963 and concluded that the main emphasis should be study of a hybrid DC/AC system. The task force report stated:

> The purpose of the program should be to provide a basis for realistic engineering evaluation of the application of HVDC (High Voltage Direct Current) for long distance power transmission in the United States, but should not duplicate work already being carried out by others. The main effort of the project would be focused upon the operation of DC lines integrated with AC systems.

In April, 1970, seven years later, John wrote the final report for EEI RP56. He restated the charge given to him as project manager:

> The broad objectives of the project were basically two fold: To evaluate the performance of existing DC lines in parallel with an AC system and then to investigate what changes might be made to improve their performance.

There were a number of reasons why this study was considered highly important by American power companies.

BIOGRAPHY OF A PROJECT MANAGER

Working as a manager of EEI RP56 evidently had brought John Dougherty a great deal of pleasure. "I've thoroughly enjoyed the experience. Running a research project on such an interesting subject has been a new wrinkle for me and I've had a lot of fun," said John.

Having served in the U. S. Navy during World War II as an electronics technician, John continued his education at Villanova, and graduated with a B.S. in electrical engineering in June, 1950. He had taken all the electronics courses and wanted to work for an electronics firm.

Jobs were scarce. Engineers were many. "People were complaining about all the engineers graduating who really ought to be truck drivers," John reminisced. No jobs were open in the Philadelphia area; finally John obtained a place with the U. S. Signal Corps and began work in New York City.

"The Korean War started late in June, 1950. Suddenly there was a great shortage of engineers. I worked, though, with the Signal Corps for seven months until they cut off the per diem allowance. It cost me too much then to work in New York, so I applied in early 1951 to an employment agency in Philadelphia, asking specifically for a contact with electronics firms. The first place they sent me to was Philadelphia Electric; so here I am!" related John.

John speculated that, if he had graduated a year later, a job with an electronics firm might have been open and he perhaps would have stayed with them just as he has with the electric company.

"Here at PE, I've always worked in that area of the company which deals with rather fundamental problems of long range significance rather than the day-to-day operations or engineering areas. First, I was in the Energy Distribution Branch of the System Development Division. This branch later became the Energy Distribution Section of the Engineering Research Division where I am today," said John.

From 1964 to 1970, the job of project manager of the AC/DC research work was a full-time assignment.

What circumstances led to John's selection? John explained, "Well, back in 1955 a vice-president of PE was U. S. representative on the DC Committee of C.I.G.R.E. (International Conference of Large Electric Companies) and, after becoming acquainted with European work with DC, he persuaded the company to begin a small study of the subject. I was the one who had some special knowledge in electronics and since converting from AC to DC and back to AC involved vacuum tubes, I was assigned the task of building a bread-board model.

"When we began to study the use of DC, very little was known. There were no good textbooks. We searched for as much information as we could find, and finally bought four years of back copies of an English magazine which dealt with DC and started reading from scratch."

By 1960, a background of information had been built up through reading and experiment and two "bread-board" models had been constructed. Other research projects had taken up John's time and interest, too. From 1960 to 1963, the work on DC lay somewhat dormant but a renewal of interest then led PE to begin negotiations with Westinghouse to do some applied research. "Then the EEI project got started," said John, "and brought everything else to a halt. I acted as a resource person for the organizing committee and, since we at PE were about the only ones among U. S. utilities who

had studied the subject very much, I was selected as project manager. For a three-year period, I was fortunate to have Vincent Caleca of American Electric Power's Service Corporation as assistant project manager."

MOTIVATION FOR RESEARCH ON AC/DC SYSTEMS

In the early days of electric power systems in America, generation, transmission, and use of power was at low voltage and DC. George Westinghouse's new AC system won out over Thomas Edison's advocacy of DC, after a rather bitter dispute near the end of the 19th century. AC had predominant advantages: less expensive, more rugged machinery and more economical transmission of power. American utilities universally adopted AC.

In the last few years, however, engineers have turned attention again to high voltage DC systems because of the following:

1. Relatively reliable, but still somewhat costly, equipment has been developed to change AC to DC (rectifiers), and invert the hi-voltage DC back to AC (inverters).

2. Cable capacitance, which limits the length of AC cables, is of no consequence to DC.

3. Less costly DC transmission lines, for the same amount of power carried, are available overhead or underground.

With present technology and costs, DC becomes more economical than AC when large amounts of power are carried (several hundred MW) and the transmission distance is estimated at 250-500 miles for overhead and 20-30 miles or more underground.

In the fall of 1963, the U. S. government was preparing to contract for building a long DC transmission line between the Bonneville Power Administration area, which is the Columbia River region of Oregon, and southern California. This line is now called the Pacific Intertie, a line 835 miles long. Companies such as Southern California Edison and Pacific Gas and Electric were partial owners and would use power provided by the new line. Yet no American utilities had had a great deal of experience with DC since the U. S. historical development was different from that in Europe. However, the government felt that, based on European experience with DC, the long distance and high power combination on the planned Intertie clearly indicated economies worth investigating.

EEI member companies agreed that this new line and perhaps possible future DC lines, overhead or underground, would depend on a rapid increase in U. S. power engineering competence in and knowledge of DC.

A Federal Power Commission report in 1966 stated:

> The Edison Electric Institute is sponsoring a $2,200,000 project to determine how a high capacity DC transmission line could be operated as part of an interconnected AC transmission system. This work is essential to establish the technical feasibility of using direct current for moving large blocks of power long distances as an integral part of the interconnected power system in this country. Successful demonstration will allow consideration of DC underground transmission as an alternative to AC underground when planning electric power systems.

Thus it was with some degree of urgency that the EEI Task Force on AC/DC systems was constituted and laid its plans.

"The budget of $2,200,000 was underwritten by the utilities and the whole project was underway in less than a year. This was pretty rapid, as things usually go. Also, we've stayed within our budget, and that too may be a little unusual!" quipped John.

John added, "Changing the engineering team every year caused some headaches. It proved difficult for companies to release quality people that way. However, we managed to work it out and the knowledge we gained about DC was spread around many companies."

CONDUCT AND CONCLUSION OF EEI RP56

After the Task Force under EEI was formed, and a Project Manager and the first year's engineering staff appointed, it was decided to move the project work to a location on the University of Pennsylvania campus.

Work began immediately on building a good model. Arrangements were made for an outside firm to begin writing a digital computer program which would represent all inputs, outputs, and system equations faithfully. By fall, 1965, the physical model was working and experimentation began.

Other work was done at the University of Wisconsin, where a simulator of parallel AC and DC transmission lines between two busses and SCR's for the converter units was made. Studies also were made on a large analog computer.

Throughout this period of six years work, John Dougherty was not only managing the project but constantly writing and giving reports to the Task Force. A complete file was kept. Journal articles were written and presented at society meetings. "Organization and communication of all the information we were collecting and learning was a big part of my job, in addition to technical matters," said John.

In June, 1970, a letter of transmittal was written by an official of EEI covering the dispatch to EEI member companies associated with the AC/DC Project of a broad report dated April, 1970 (the Table of Contents of which is shown in Exhibit 1A of Appendix A), which summarizes research conduct and conclusions. Exhibit 2A describes the physical model and gives a diagram of it. Exhibit 3A gives a listing of results of the research.

It was found to be difficult and expensive to get results from the larger digital computer program which compared favorably with the actual tests on the model system. The computer program was to be usable for large systems and specifically the Pacific Intertie. Apparently this first attempt to incorporate DC into existing AC system programs was too large a project to begin with.

"We (the project staff) finally decided to write a small systems (10-bus) load flow and transient stability program. These were written in Fortran IV for the IBM 360/44 and have been checked by comparison with tests on the Philadelphia model system," recounted John.

DC subroutines can be used with existing AC transient stability programs and these subroutines represent well the DC line and converters at the terminals.

AN OBSERVATION CHALLENGING ENGINEERING SKILL

Exhibit 3A shows that many things were learned from the research project. Among them was the fact that "DC line loading may be modified in such a way to provide damping of power swings and to enhance stability of the AC system."

In September, 1967, in a memo entitled "Interesting Items," John reported that various types of AC system disturbances--sudden removal of a generator, sudden addition of

another load, or an AC transmission line short-circuit to ground--had been deliberately imposed. By controlling the flow of power over the DC link in the proper way, it was found that the transient disturbances on the AC system could be rapidly damped out. (See Exhibit 4A.)

"At first," John explained, "we simply varied the power flow over the DC link by manually turning the knobs on the DC current controllers, and we observed that the AC system was quickly restored to a stable condition."

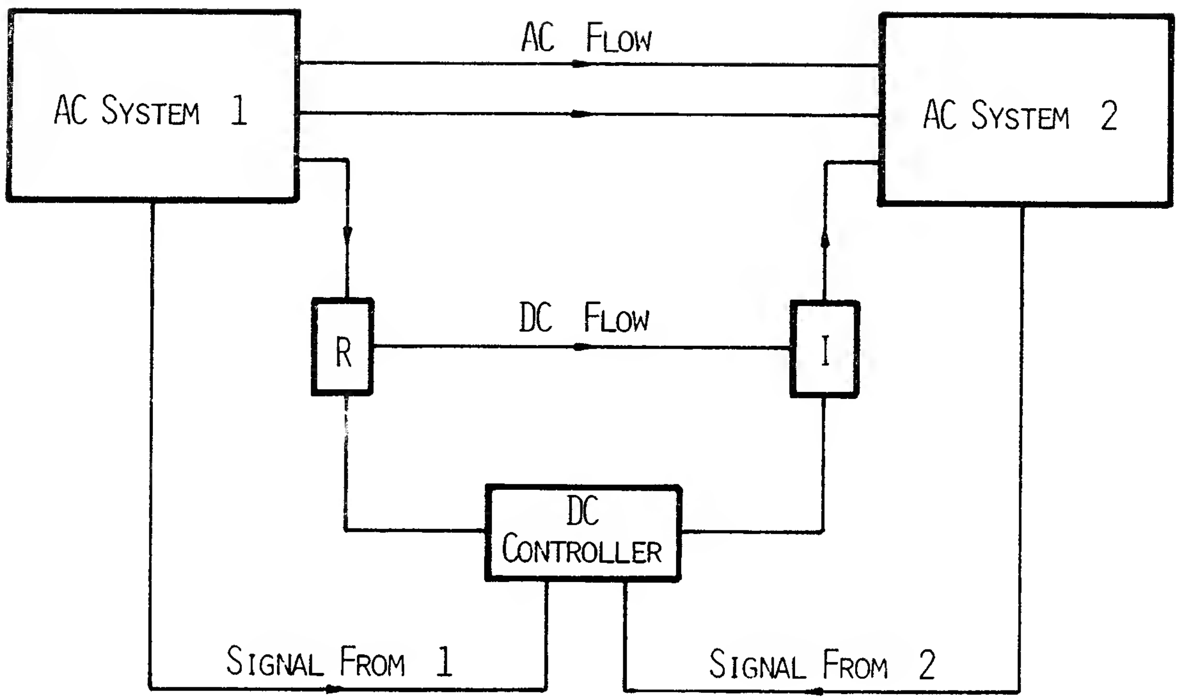
John added that then the effort began to concentrate on completion of the total control system so that the magnitude of the AC disturbance itself could be used as a source of error signal to control the DC line.

Such a control system would obviously gain in importance as the use of DC in actual practice increased. The Pacific Intertie was under construction at that moment. John wrote in the fall of 1967:

> On October 16 and 17, the EEI Task Force meeting will be held in Vancouver, British Columbia. The first modern DC line in North America is now nearing its service date between the mainland and the Island of Vancouver and is of particular interest to us since it will be the first DC line in parallel with AC lines. In fact, quite by accident, the EEI model resembles this installation as though it were designed for it. Both our model and the Vancouver installation involve one DC line and two AC lines as parallel ties between two AC systems.

The block diagram on the following page will aid in understanding. A disturbance in either AC-1 or AC-2 or on the interconnecting AC lines was sensed and used to operate a circuit (DC current controller) which varied the amount of DC current--proportional to DC power if voltage were constant, of course--handled by the DC rectifier and inverter. The important questions to be answered now became:

1. What sort of signals (systems parameters) should be used to control the DC power flow?



Block Diagram of Model System

2. How would the circuits be designed?

3. What would be the test results?

APPENDIX A

EXHIBIT 1A

ECL 195A

(COURTESY OF THE EDISON ELECTRIC INSTITUTE)

REPORT

OF THE

EDISON ELECTRIC INSTITUTE

AC/DC SYSTEM OPERATION
RESEARCH PROJECT
(EEI PROJECT RP56)

April 1970

TABLE OF CONTENTS

EXHIBIT 2A

(EXCERPTED FROM REPORT OF EEI RP56, APRIL, 1970)

THE PHILADELPHIA MEDIUM POWER SYSTEM MODEL

Summary of Design and Construction

A major share of the effort by the Task Force and Project Staff was directed toward the design, construction, and investigative use of an AC/DC system model. This facility is located on premises of the University of Pennsylvania under a ten year (maximum term) agreement. When the laboratory was no longer required for the EEI studies it was turned over to the University December 16, 1969.

Before preparing designs and specifications for this model, the project staff investigated all models of various types known in this country and abroad, and prepared cost estimates of models of various sizes.

By the summer of 1964 these investigations led to a Task Force recommendation to proceed with a model based upon utilizing 50 kw, 3 phase mercury tube bridges in a simple system arrangement capable of representing two independent AC systems interconnected by a bi-polar DC line and two AC lines. The recommended construction included a building to house the model and the project staff.

Design Features of the System Model

Many special features were included in design of the model to simulate realistically the performance of a large high-voltage system. Fig. 1 shows the main components in single line form. There are three AC generators driven by DC motors. These units are provided with flywheels to represent typical inertia constants of large steam units. The DC drive motors simulate the response of modern turbo-alternators through the use of analog components representing the turbine and boiler response characteristics.

The generator excitation systems likewise are representative of the response of modern large machines. AC transmission lines are simulated by L sections, each equivalent to 25 miles of 500 kv aerial transmission line. The DC line sections are also equivalent to 25 miles of ± 375 kv aerial transmission line. Typical model studies were conducted with two AC lines 250 and 300 miles long, and one DC line 300 miles long.

The AC/DC converter units are 50 kw, 3 phase, double-way bridges using small mercury-pool, excitron type tubes with many characteristics similar to the tubes used in actual DC transmission installations. The internal tube voltage drop does represent a larger proportion of the 500 volt output than in the case of the large power high voltage tube.

Control equipment for the AC/DC converters was furnished by ASEA and has features similar to the controls on commercial installations. These include sensing and protection for commutation failures, arc-backs, DC line faults, AC system undervoltages, etc. The control, as furnished, was for the "constant-current" mode of operation. Subsequently, other control equipment arrangements were investigated.

The converter transformers have variable impedances and an 11-step manual tap changer. The DC smoothing reactors have both variable inductance and variable saturation characteristics. The DC line terminals are also provided with banks of capacitors for reactive supply and harmonic filtering. Load representation for the model includes both static and rotary units. Shunt reactors provide realistic system power factors.

A high degree of flexibility in system configuration is provided by a series of plugboards interconnected by ring busses. Control and instrumentation is in a centrally located control room with four consoles. Three of these are used for the operation of generation equipment, AC/DC converter equipment, and the load units. The fourth console provides test instrumentation for all aspects of the model including oscillographic equipment, and a digital time sequence programmer.

Future Status of the Model

On December 16, 1969, the Philadelphia model was transferred to the University of Pennsylvania under an agreement whereby the University will administer, maintain and operate this laboratory with financial support from Project funds. The agreement is subject to annual review or cancellation until its termination on Feb. 8, 1975. During this time the model will be available for use by educational institutions, the EEI and member companies, manufacturers and others. Fees collected by the University from those using the model will for the most part reduce the cost to the EEI for support of basic operation and maintenance expense.

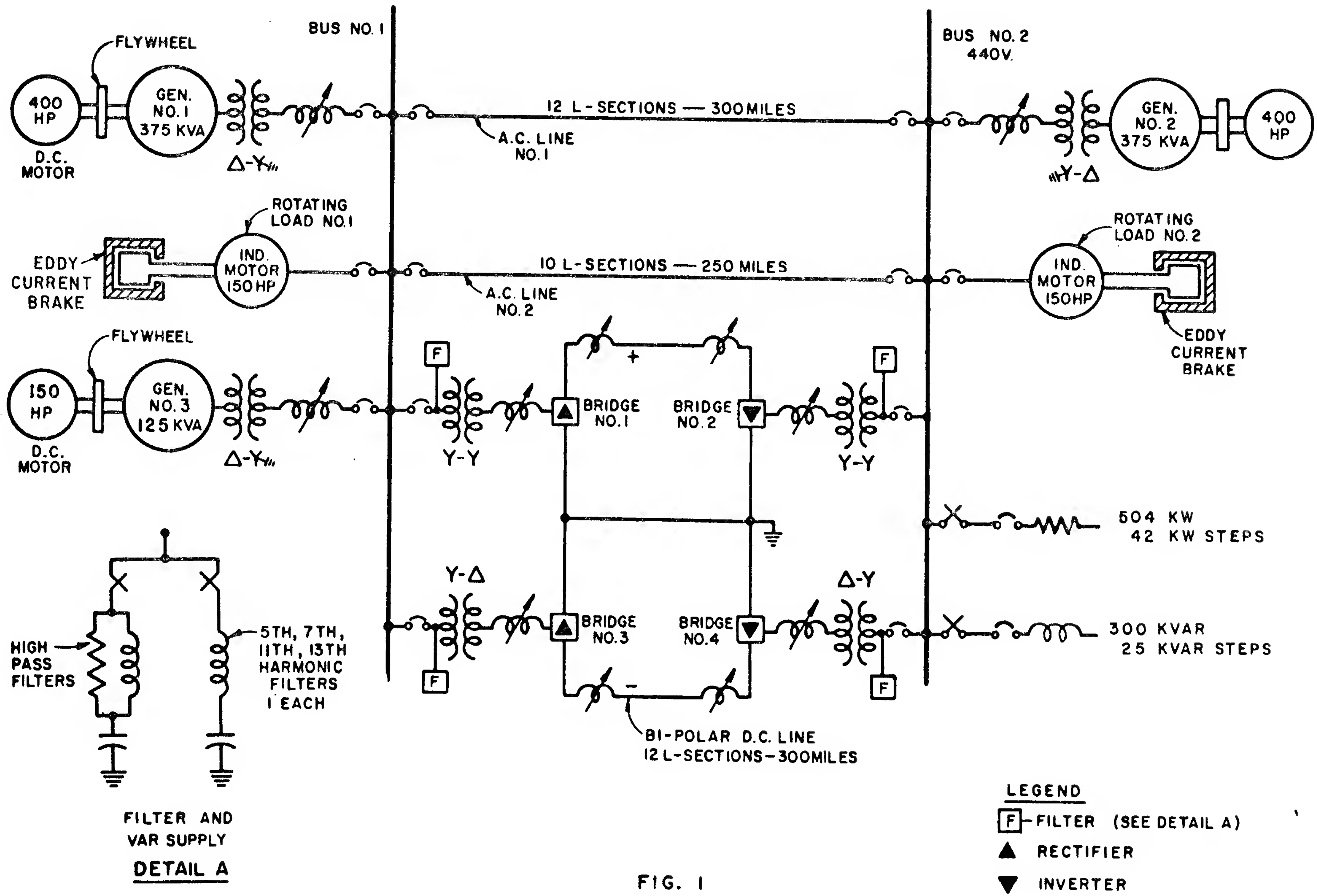


FIG. 1

SINGLE LINE DIAGRAM

EXHIBIT 3A

(EXCERPTED FROM REPORT OF EEI RP56, APRIL, 1970)

RESULTS OF RESEARCH INVESTIGATION

Summary of Conclusions

A DC transmission line will operate very satisfactorily in parallel with an AC system.

A DC line operating in parallel with an AC system is relatively undisturbed by trouble on the AC system.

Control and protective features on a DC line permit very rapid clearing of transient faults and re-energization of the line.

Transient overvoltages resulting from faults on DC lines do not exceed 1.7 times normal DC voltage on the basis of the line simulations used. This confirms the value calculated theoretically.

DC line loading may be modified to provide damping of power swings and to enhance stability of the AC system.

A three-terminal or tapped DC line can be controlled and operated with existing control equipment. The performance of such a multi-terminal DC line would be improved by the availability of a DC circuit-breaker.

If the DC terminal used to control the DC line current has a weak AC bus (short-circuit ratio of 4:1 or less) it may cause steady-state stability problems in the DC controls.

A 10-bus AC/DC load flow and transient stability program was developed with complete representation of a two-ended DC line including responsive controls.

EEI D-C TRANSMISSION PROJECT
3221 Walnut Street

September 7, 1967

Interesting Items

A paper has been prepared, coauthored by John J. Dougherty and Vincent Caleca, for presentation at the d-c session of the C.I.G.R.E. Conference in Paris, France. The paper describes briefly the laboratory facility and presents an analysis of test results of the interaction between a-c and d-c systems during a-c system faults, and a study on d-c line overvoltages. At the Task Force meeting in Philadelphia on August 10 and 11 the Task Force approved attendance at this meeting for J. J. Dougherty and recommended that arrangements also be made to visit people active in this field in England and Germany.

At this Task Force meeting we also had a report from Mr. J. E. Conner of Southern California Edison concerning the problem of consequent arcbacks in ASEA tubes. The tubes in the New Zealand project are still experiencing difficulties in this respect, and an elaborate program has been initiated in Sweden to satisfy the participants in the Pacific Northwest-Southwest Intertie that the tubes delivered for that project will not have this problem. The various theories concerning this arc phenomenon generally agree that it is primarily caused by minute "dirt" remaining in the tube, but it has only become a serious problem since the tube ratings (voltage and current) have been pushed to higher values. Efforts are being made to increase the "bake-out" time and temperature to minimize any resultant foreign particles in the tube.

Tests have been made on the Philadelphia model analyzing various types of a-c line faults and the resulting effects on the d-c system. Step load changes and generator dropping tests have also been performed. At the present time work is in progress to develop a modification of the d-c constant current control to permit the d-c line to sense the needs of the a-c system and vary power flow to damp a-c system swings. Tests in which the proper current order changes to the d-c line were artificially provided, have demonstrated the potential capability of such a control system.

As previously reported, no correspondence between the performance of the model and the G.E. transient stability program has yet been achieved. A difference of opinion exists on the cause of this lack of agreement, and an impasse seems to have been reached in which, at least for the present, no serious efforts are being made to resolve the problem.

John J. Dougherty

Project Manager

JJD:mhs

ECL 195B

ENGINEERING CASE LIBRARY

RESEARCH ON HYBRID AC/DC ELECTRIC POWER SYSTEMS AND SYSTEM STABILITY TECHNIQUES

Part B

Design of DC Control System for Improved Stability

INITIAL TESTING -- REMOVAL OF DC POWER FLOW STEPPING SWITCH

John related, "After the model system was working O.K., we began to test its response to disturbances. We would set a certain fixed level of DC power flow by manual adjustment of the DC current order control, initiate some kind of disturbance, and observe." The staff engineers noted only a slightly improved transient stability. (See Figure 1 for the arrangement at this time--late 1966.)

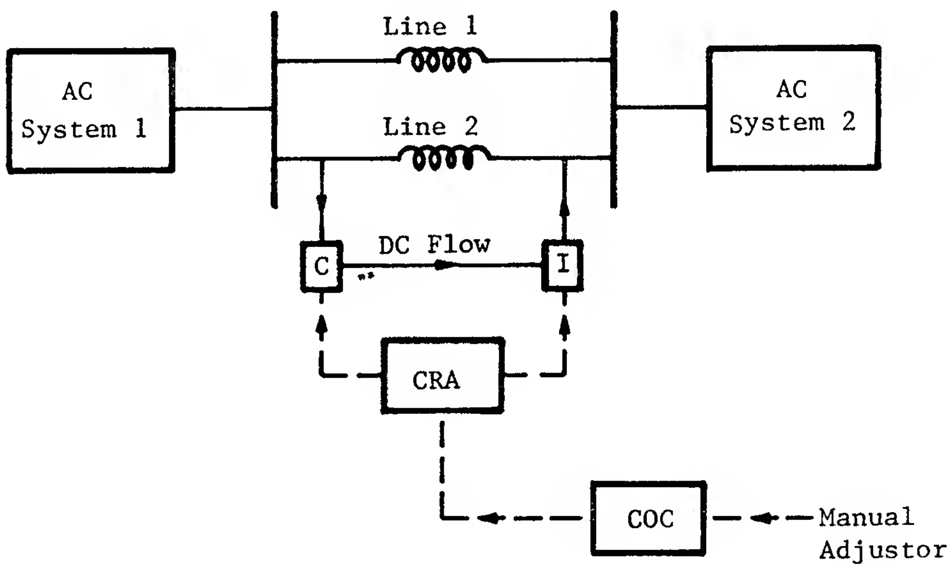


Figure 1. Original Set-up

"While testing, we found that the DC converters-inverters could go from full ON to full OFF very rapidly, almost instantaneously, actually. This led to our by-passing a so-called 'stepping switch' on the panel which was camouflaging the speed of response of the DC link," John said.

Why was the stepping switch, which enabled the operator to bring the DC line power up to its desired rating in a series of discrete increments, used at all?

John explained, "Well, the builders evidently felt a slight probability that some unwanted excursion-type of phenomenon would happen in the mercury arc rectifier tubes if the maximum response rate were called for. Also, in prior operation of DC ties between otherwise isolated AC systems--say, for example, like the Gotland Island-Sweden Line, which feeds a relatively small system--it was undesirable to suddenly dump a large amount of power into the island system. So there was a historical reason for this switch, which acted like a throttle. However, there was now a reason to take it out as it was not needed for parallel AC/DC lines."

Taking out the stepping-switch control gave the research group an idea:

"The DC part of the system was so fast," said John, "that we thought, 'My! If it knew there was an AC disturbance and had the transmission capability and a proper location in the system, it could change its power flow and damp out that disturbance, and it could do it before the AC system even had a chance to respond to the fault!' "

It was found that as much as 100 KW could be dropped suddenly from the AC lines and the DC link could pick it up again in less than 20 milli-seconds. Since the AC system oscillated under a normal transient condition at about a one-second period, the controlled AC system hardly noticed the disturbance.

"We determined the amount of DC control voltage to cause a certain DC power flow and rigged some batteries, switches, and relays so that this amount of power could be dropped suddenly from the AC lines and picked up by the DC link. We found that the AC system swings could be damped out quickly, or never even allowed," John related.

FIRST MODIFICATION -- θ CONTROL

The first control signal used was the angular difference between the rotors of the two generators, one in AC system-1, the other in AC system-2. In steady-state, the angle was constant since the generators were synchronized. The angle changed as system loads changed.

A method was devised to measure this angular difference and convert it to a DC voltage proportional to the angular difference. The result was a DC voltage of about 0-20 volts range, sufficient to drive the DC power line from no-load to full-load. The arrangement is shown in Figure 2.

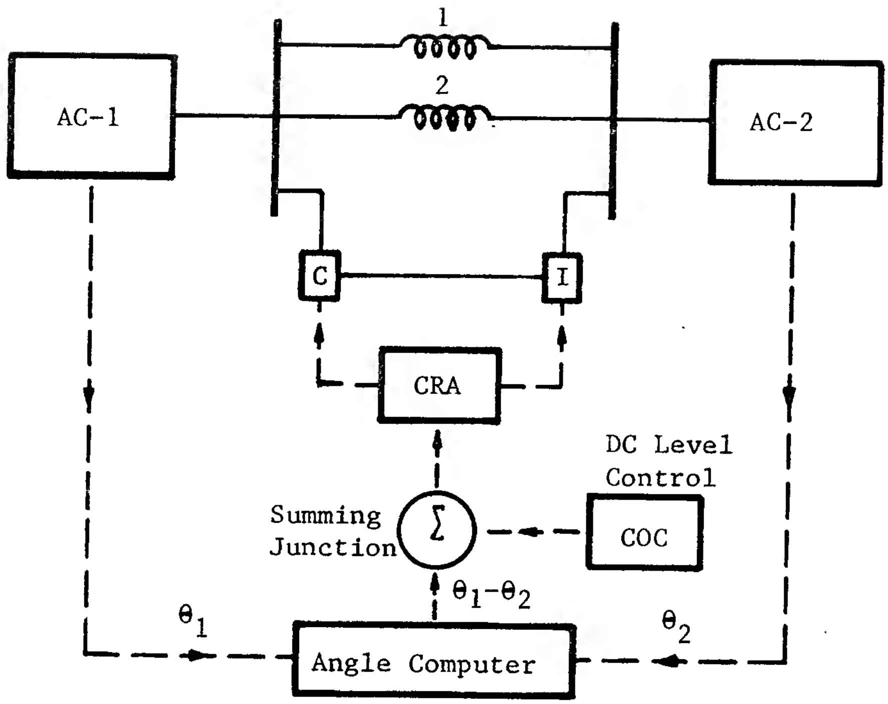


Figure 2. Set-up with Angle Computer

John wrote in a report to the Task Force in October, 1967:

> Work has continued on the Philadelphia model to develop modifications of the d-c constant current control that would permit the d-c line to be dynamically responsive to a-c system disturbances in such a manner as to damp an a-c system swing. One such control in which the angle between machine rotors was used as an input to the d-c current order has been tried out and works well under some circumstances but is not acceptable under other types of disturbances.

"We began to think of using $d\Theta/dt$ control instead of Θ for two reasons. Normally $d\Theta/dt$ is maximum when Θ is

minimum, say, for a sine wave. This meant we could get a faster response just as Θ started to change and get more response then," said John.

SECOND CHANGE -- DERIVATIVE CONTROL, RC DIFFERENTIATOR

One of the project engineers, Jeffrey Sekerke from Consumers Power in Jackson, Michigan, began to work on this and first tried a simple RC differentiating circuit attached to the angle computer. (See Figure 3.)

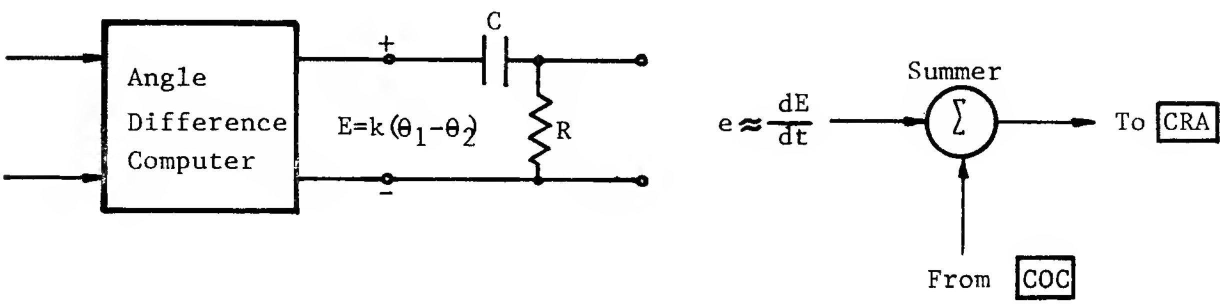


Figure 3. Original $\frac{d\Theta}{dt}$ Circuit

This was found to work much better--the DC link began to act truly as a strong transient damping device.

However, the frequencies involved were so low that it was difficult to get perfect differentiation, e.g., a 90° phase shift between E(t) and e(t) for a pure sine wave. Sekerke suggested using solid-state operational amplifiers in differentiator configuration.

A THIRD TIME AROUND THE DESIGN LOOP -- OPERATIONAL AMPLIFIERS

"Jeff designed a derivative amplifier using standard op-amps and the manufacturer's handbook," recounted John, "and came up with a much better circuit." (See Figure 4.)

The staff now had an e(t), an output voltage proportional to the rate of change of angular difference between the two AC systems.

John recalled that Jeff's first choice of a catalog op-amp did not have proper input and output impedance levels, but a second choice was ordered and it worked properly.

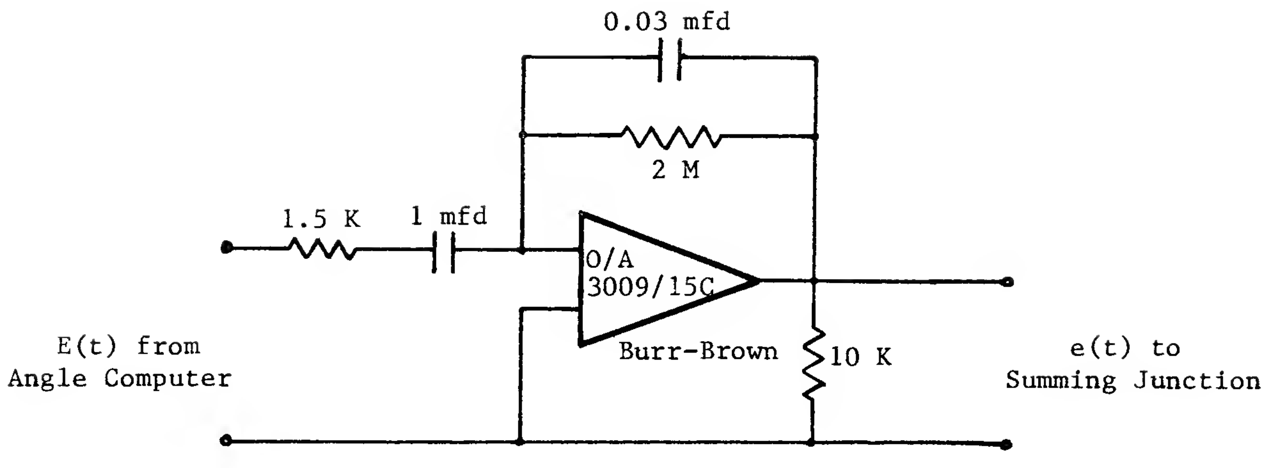


Figure 4. First Derivative Amplifier

About this time another engineer, Thomas Hillesland of Pacific Gas and Electric, joined the RP56 staff. He, Sekerke, and others began further testing of the control characteristics of the new dΘ/dt circuit, and it was found that, though much improvement was achieved, there was still only 75-85° phase shift in the differentiator. Tom began to design a filter to give the additional phase shift desired and came up with the circuit in Figure 5.

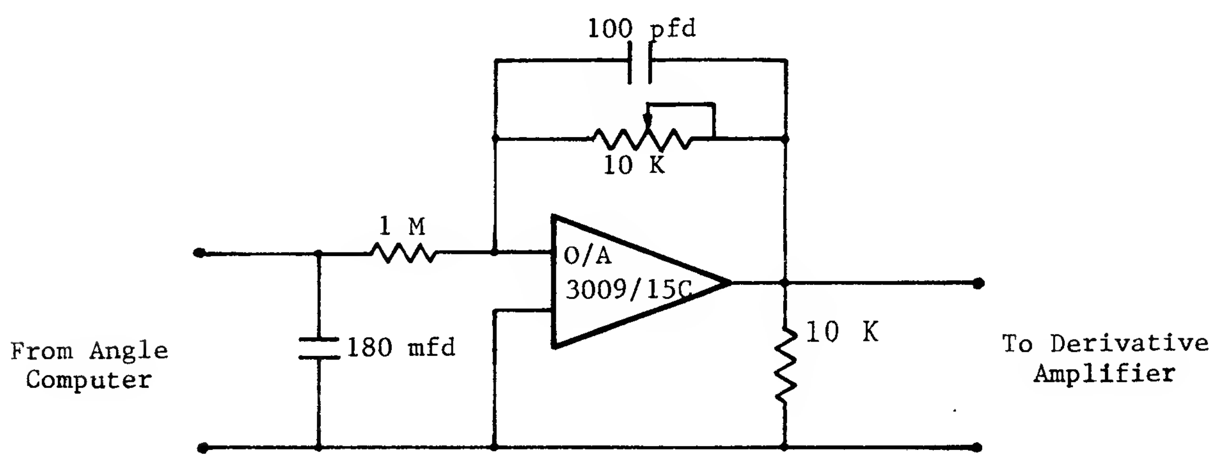


Figure 5. Derivative Amplifier Modified

Further testing then ensued and the need for still more change was seen.

FOURTH MODIFICATION -- LIMITS CIRCUIT

It was found that 0-20 volts into the CRA drove the DC link practically over its entire power range, 0-100 KW. If the steady-state DC power level was set at 50 KW, with about 10 volts from the COC, for example, then the possibility existed of overdriving the CRA when a too-large DC signal from the dΘ/dt circuit was received--or, on the other hand, driving the DC power to cut-off should the dΘ/dt signal be more than 10 volts negatively.

Hillesland investigated the problem and decided to incorporate another circuit which would make it possible to set limits on the positive and negative voltage swings of the dΘ/dt signal voltage. Figure 6 shows the idea.

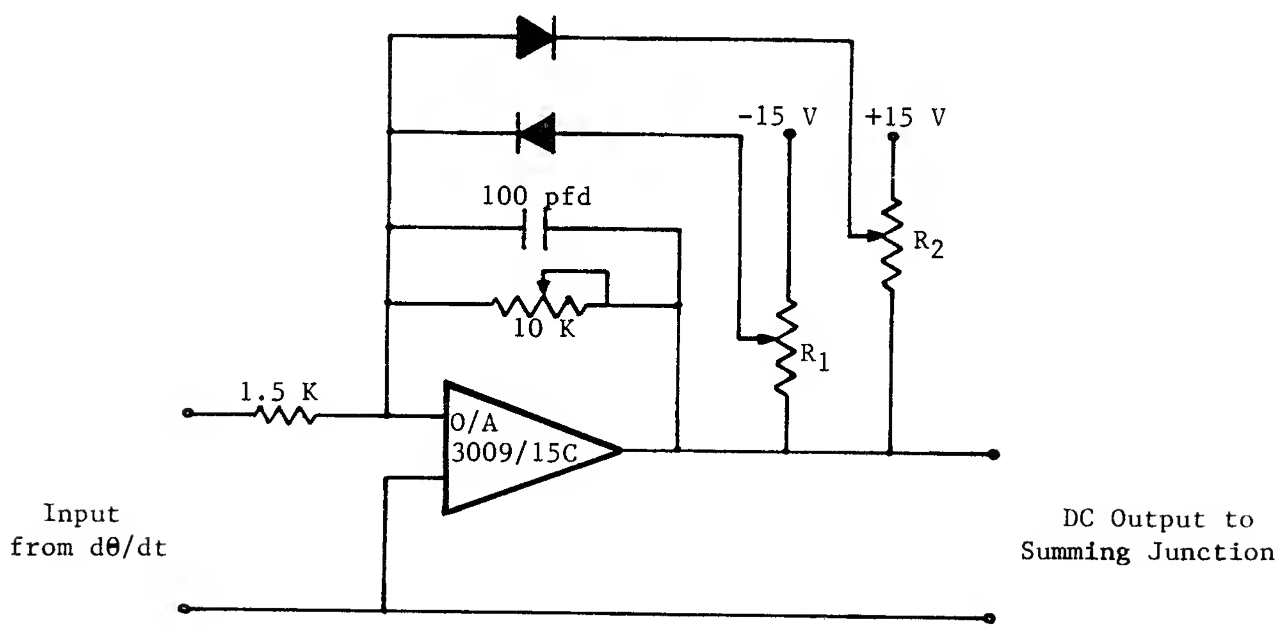


Figure 6. Derivative Amplifier with Limits Circuit

Analysis of the circuit shows R_1 and R_2 will independently set the negative and positive voltage swing limits,

respectively. Now, if the steady-state DC current order voltage were for 25% load at +5 volts, the negative dΘ/dt voltage limit was set for -3 volts, leaving a +2 volt signal to give 10% of full load DC power, avoiding cut-off. The positive dΘ/dt voltage limit could be set for +15 volts and the DC link could then be driven up to full load.

MORE TESTS AND CONTROL OPTIMIZATION

During the latter half of 1967 and through 1968, the research staff continued with many tests and improved the control system progressively. The staff was joined by a new engineer, Harold Kirkham, who conceived several improvements and incorporated them into hardware.

"The job of writing all the memos and reports seems always to take more time than doing the work itself," John noted. He and Hillesland wrote a long report to EEI, dated March, 1968. This report was used as a basis for a technical paper for the IEEE Winter Power Meeting, January, 1969, but during 1968, additional tests were made and the derivative control circuit was modified again. (See Figure 1B in Appendix B, and Reference 3 in the bibliography.)

John said, in reference to all the changes made in the dΘ/dt circuit, "It's very seldom we can say to do this or that and solve a problem. Another problem comes up. So we solve that one. It grows like Topsy. After we finish, we have something that will work, but then someone can start all over and maybe eliminate half the parts!"

"With all the talk about optimization, I sometimes doubt we ever really do optimize anything. It's always imperfect, always a compromise between theoretical perfection and what we can obtain for a price," John added.

ANOTHER CONTROL SIGNAL?

The research group considered another possible control parameter since one disadvantage of dΘ/dt control was that after the disturbance was over, the DC power flow would be at its original level. It might, they reasoned, be best to program a change in the DC level to take up or compensate for the AC power flow changes so that over-all power flow would be kept constant.

This variation, however, was never actually put into hardware, although certain tests demonstrated the feasibility of storing specific current orders at various points and using this information to control the dynamic DC system.

CONCLUSION OF MAJOR TEST SERIES

John wrote (see Reference 3):

> In most of the tests the DC line was loaded to one-half its thermal rating and the AC lines to approximately one-half their surge impedance loading. These levels were chosen to create a system which would be only marginally stable for a disturbance involving momentary interruption of one of the AC lines.

The effectiveness of the DΘ control is shown in the figures in Exhibit 1B, Appendix B. We can see clearly that the system goes unstable in Figures 4 and 8 but use of DΘ control quickly restores stability, as shown in Figures 6 and 9, respectively. These oscillograms pertain only to one type of fault, sudden loss of AC line 1, although the RP56 staff investigated many other kinds of disturbances.

It was confirmed that both steady-state and transient stability limits were increased by the DC link. Also the staff reported that, even if the disturbance were a temporary outage of the DC line itself, its dynamic response was fast enough to maintain stability upon re-starting the line.

CONTINUING WORK

John pointed out that further work has been and will be done to investigate other variations. (See Reference 4 in the bibliography.) "The lab will be available for use after arrangements are made with the University of Pennsylvania," he said.

What significance does this EEI RP56 hold for the power industry in the U. S.?

"Well," John explained, "our model system is so similar to the Vancouver-Vancouver Island tie, where two AC lines are paralleled by a DC link, that such a dΘ/dt control scheme could perhaps be used there. Also we might learn to operate our AC lines, say for the Pacific Intertie, at higher ratings since the stability problem could be partially alleviated. In more complex systems, other control schemes based on the AC/DC hybrid idea could be used."

The stability problems for power system engineers have become more serious as longer transmission lines and interconnections between systems in the U. S. have come into being--reducing line inductive reactance by paralleling AC lines or using "bundled" conductors has helped. However, the problem of stability, especially when more demands are placed on power systems in situ, has become more serious. Much research is being done, challenging work for an imaginative engineer. Perhaps the use of more DC in the U. S. will be a part of the solution to the stability problem.

Supplements 1B and 2B of the appendix provide the reader with background material to aid in understanding the concepts of stability in a power system and the way the $d\Theta/dt$ control signal introduces a damping term into the system dynamic equations.

APPENDIX B

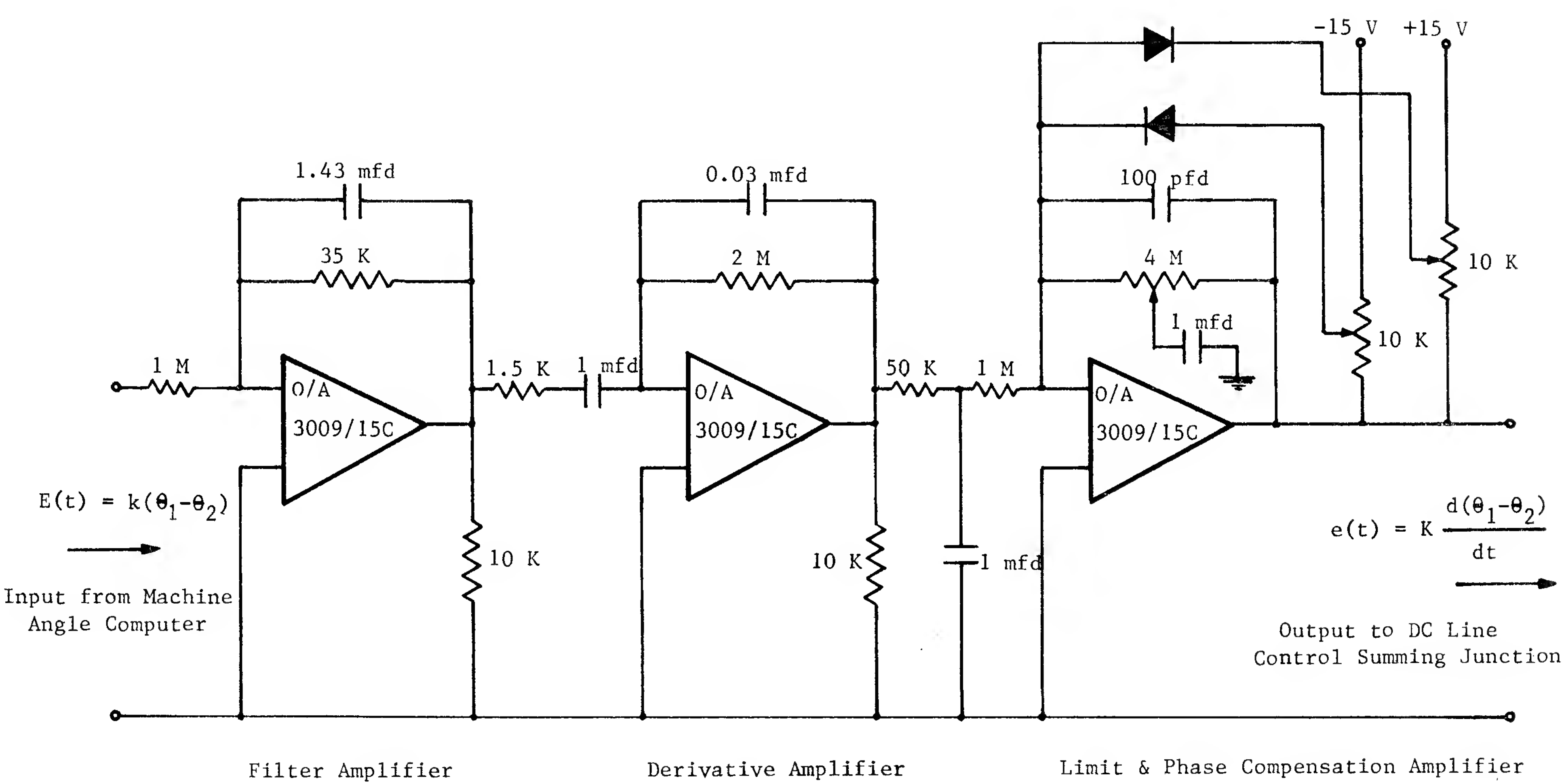


Figure 1B. "Optimized" $\frac{d\Theta}{dt}$ Control Circuit.

(Ref. 3 in the Bibliography)

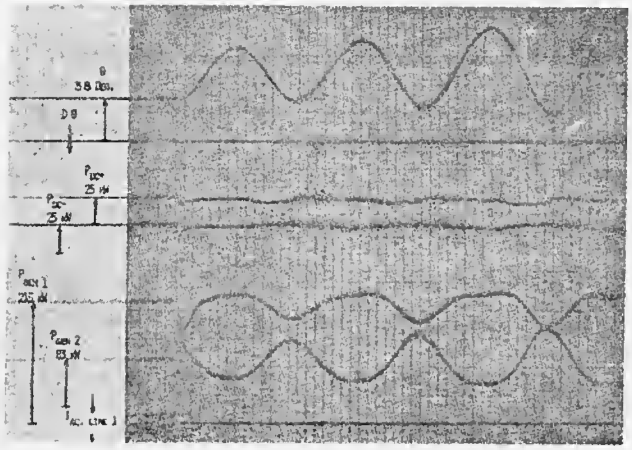


Fig. 4. Remote AC Line Fault, No Reclosure. DΘ Off.

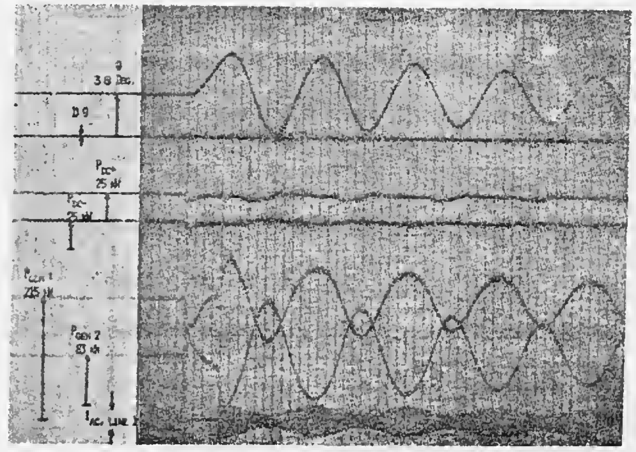


Fig. 5. Remote AC Line Fault and Reclosure. DΘ Off.

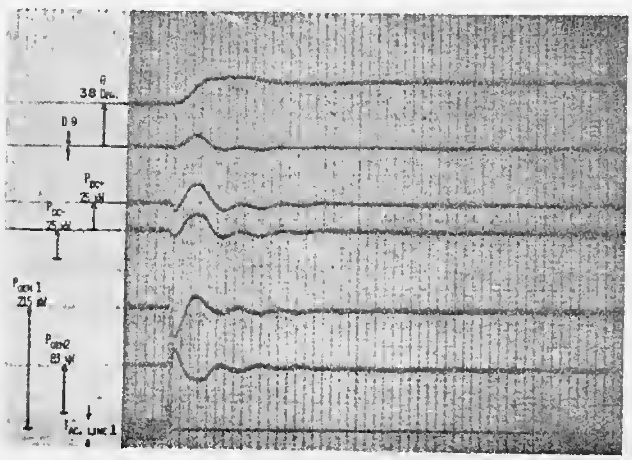


Fig. 6. Remote AC Line Fault, No Reclosure. DΘ On.

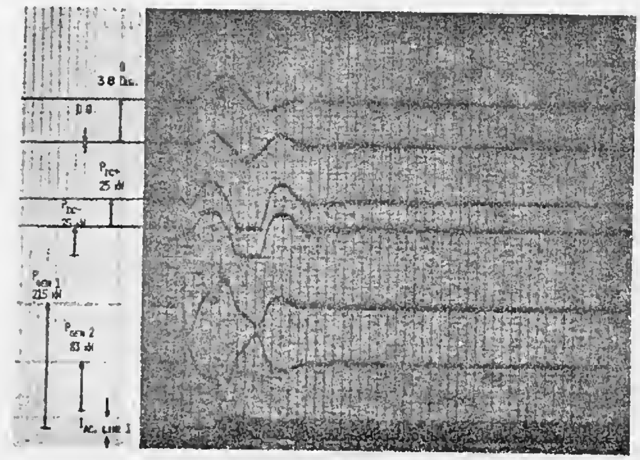


Fig. 7. Remote AC Line Fault and Reclosure. DΘ On.

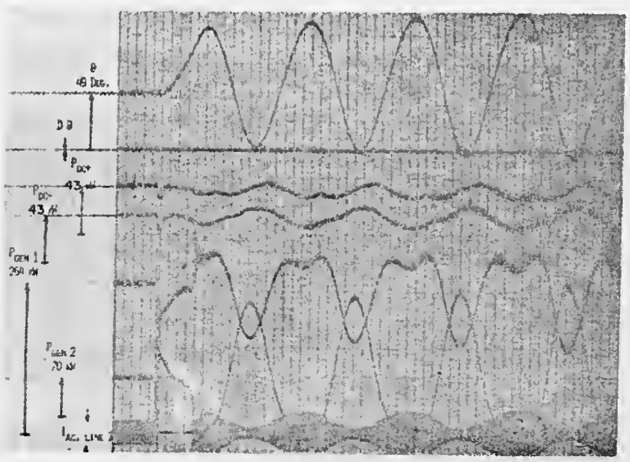


Fig. 8. Remote AC Line Fault and Reclosure. DC Line at 90% of Rating. DΘ Off.

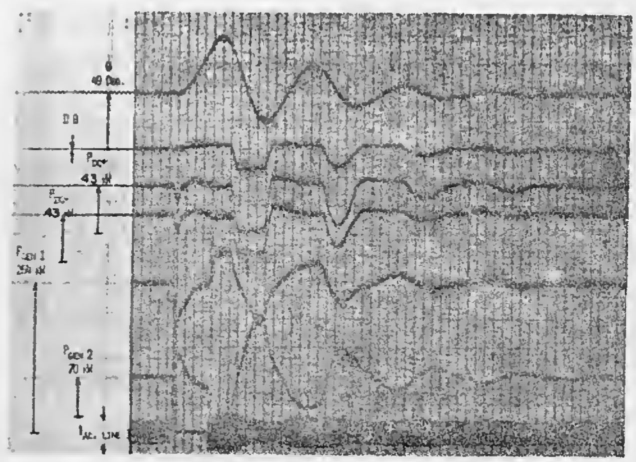


Fig. 9. Remote AC Line Fault and Reclosure. DC Line at 90% of Rating. DΘ On (10% & 110% Limits).

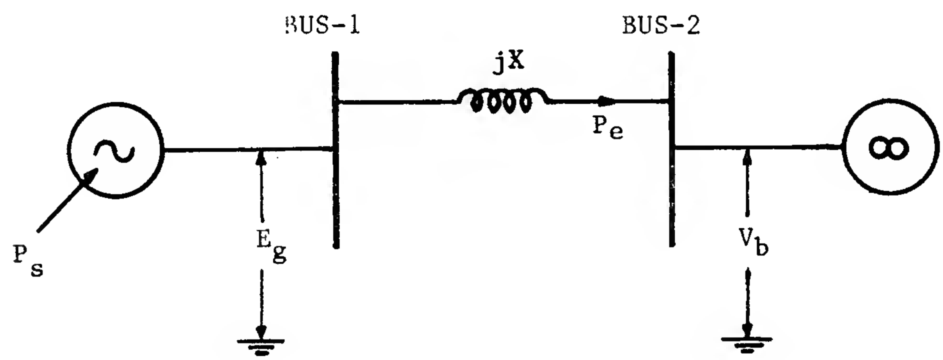
(Figures above are excerpted by courtesy of I.E.E.E. TRANSACTIONS from Reference 3, pgs. 4-5; time scale divisions - 100 milliseconds.)

SUPPLEMENT 1B

POWER SYSTEM STABILITY -- AN APPROXIMATE MATHEMATICAL ANALYSIS

A power system, including motors, generators, loads, and interconnecting lines, when subjected to a sudden disturbance--sudden loss or addition of a mechanical or electrical output or input--will either recover after a few moments and continue to operate at a slightly-changed level or will not recover and will go into wild, undamped oscillation, eventually perhaps, damaging equipment. The following is a greatly-simplified analysis but shows the important features. The power system engineer must, of course, design the system to be stable under expected disturbances.

We assume a one-line diagram of a synchronous generator connected to an "infinite" bus through a transmission line of reactance, jX.

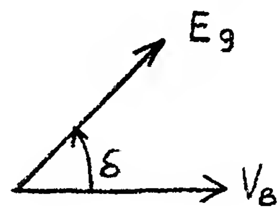


By definition, an infinite bus is a line whose voltage phasor is constant in both amplitude and angular velocity ($\omega_s = 2\pi f = 2\pi x60 = 377$ rad/sec.). We ignore the reactance of the generator, X_g, which could be inserted between the generator and bus-1, since its inclusion is not required to bring out the essential points of this analysis. P_e is the real power flow into the ∞-bus; P_s is the mechanical power input to the generator from its prime mover. In steady-state, ignoring all mechanical and electrical losses, $P_s = P_e$, and the generator rotates at synchronous

speed corresponding to 60 H_z at its terminals. Of course, depending on the machine construction, the angular velocity of the generator rotor is proportional to the angular velocity of the terminal voltage phasor, or

$$\omega_R = k\omega_g \qquad (\omega_g = 377 \text{ rad/sec.})$$

Referring to the phasor diagram below



we write, for the complex power from the generator,

$$S_g = E_g I_g^* \qquad \text{(all phasors)}$$
$$= P_g + jQ_g \qquad \text{(KW + j KVAR)}$$

and since

$$I_g^* = \frac{E_g^* - V_b^*}{Z^*}$$

and defining δ = power (or torque) angle

$$= \angle E_g - \angle V_b$$

we obtain the following for the real power flow, after some complex algebra and simple trigonometry,

$$P_g = \frac{|E_g| \cdot |V_B|}{X} \sin\delta \qquad \text{(MW)}$$

$$Q_g = \frac{|E_g|^2}{X} \qquad \text{(MVAR)}$$

Here, if the voltages are line-to-neutral KV and X is a line value, the results are phase mega-values. Also, the reactive power does not enter into this analysis, so henceforth it is ignored.

Now, in steady-state,

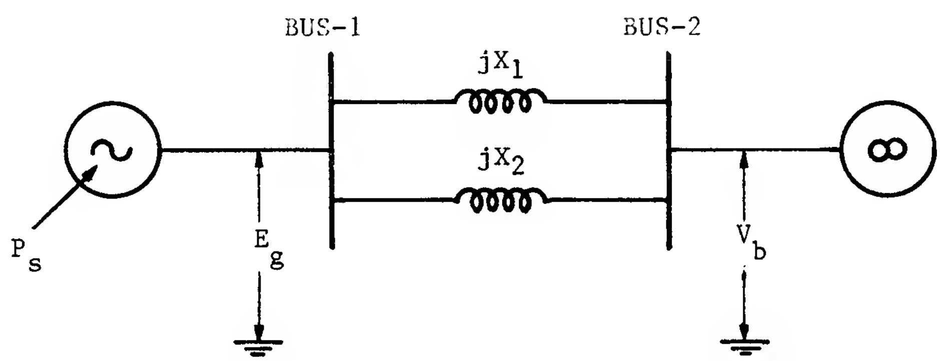
$$P_s = P_g = P_e$$

and there is a certain amount of stored kinetic energy in the rotating iron mass, usually mega-joules,

$$W_R = \tfrac{1}{2} I_R \omega_r^2$$

where I_R is the moment of inertia.

Assuming $|E_g|$ to be constant, the real power flow can only be increased by speeding up the generator for a period of time, i.e., by applying greater shaft torque. The E_g phasor advances, sin δ increases, and after the generator delivers the required power, synchronous speed is again reached. We also see that more real power can be delivered for a given δ if the reactance of the line is reduced, which is one reason for paralleling two AC transmission lines as shown.



Since power is energy rate of change, any change in shaft power input or electrical load will be accompanied by a change in the generator's kinetic energy, or

$$\frac{d}{dt}(W_R) = P_s - P_e$$

Before any disturbance, $P_s = P_e$ and W_R is constant. A change in either or both will cause an increase or decrease in generator speed and K.E. We intuitively expect that, after a time, the generator will be at synchronous speed and $P_s = P_e$ again, but each will have new values and δ will have increased or decreased.

We have

$$\frac{d}{dt}\left(\tfrac{1}{2} I \omega_R^2\right) = P_s - P_m \sin\delta$$

where

$$P_m = \frac{|E_g| \cdot |V_B|}{X}$$

Now

Θ_g = total angular displacement of generator voltage phasor

Θ_B = total angular displacement of ∞-bus voltage phasor

and we have

$$\Theta_g = \Theta_B + \delta$$

$$= \omega_s t + \delta$$

so that

$$\omega_g = \frac{d\Theta_g}{dt} = \omega_s + \frac{d\delta}{dt} = \frac{\omega_r}{K}$$

Therefore

$$\omega_r = K\,\omega_s + K\,\frac{d\delta}{dt}$$

$$\frac{d}{dt}(\omega_r^2) = 2\omega_r \frac{d\omega_r}{dt} = 2\omega_r \cdot K \cdot \frac{d^2\delta}{dt^2}$$

and

$$\frac{d}{dt}\left(\frac{1}{2} I\,\omega_r^2\right) = \frac{1}{2} I \frac{d\omega_r^2}{dt} = I\,\omega_r\,K\,\frac{d^2\delta}{dt^2}$$

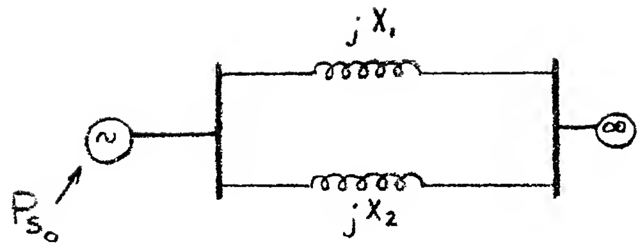
$$= K^2 I \left(\omega_s + \frac{d\delta}{dt}\right)\left(\frac{d^2\delta}{dt^2}\right)$$

We now have the important equation (the "Swing" equation) shown here

$$K^2 I \left(\omega_s + \frac{d\delta}{dt}\right)\left(\frac{d^2\delta}{dt^2}\right) = P_s - P_m \sin\delta$$

which is a non-linear differential equation. It may be solved exactly only by analog or digital computers (with the initial condition, $\delta = \delta_o$, $\dot{\delta} = 0$, and $P_{s_o} - P_{m_o} \sin \delta_o = 0$). We now seek to solve this equation for two cases.

CASE I: The system is in steady-state and suddenly line-2 is removed. Shaft power input is constant at P_{s_o}.



<u>Before</u> the event: $t<o$

$$K^2T\ (\omega_s + \frac{d\delta}{dt})\ (\frac{d^2\delta}{dt^2}) = P_{s_o} - P_{m_o}\sin\delta = 0$$

$$P_{m_o} = \frac{|E_g|\cdot|V_B|}{X_p} \text{ where } X_p = \frac{X_1X_2}{X_1 + X_2}$$

$$\delta_o = \sin^{-1}\frac{P_{s_o}}{P_{m_o}}$$

<u>After</u> the event: $t \geq o$ and initial conditions are $\delta(o) = \delta_o$, $\dot{\delta}(o) = 0$.

$$K^2I\ (\omega_s + \frac{d\delta}{dt})\ (\frac{d^2\delta}{dt^2}) = P_{s_o} - P_m\sin\delta$$

The equation may be linearized by assuming $\frac{d\delta}{dt} << \omega_s$ (the generator speed does not vary greatly) and both the initial angle δ_o and the post-disturbance fluctuations about it are so small that $\sin\delta \simeq \delta$. Therefore

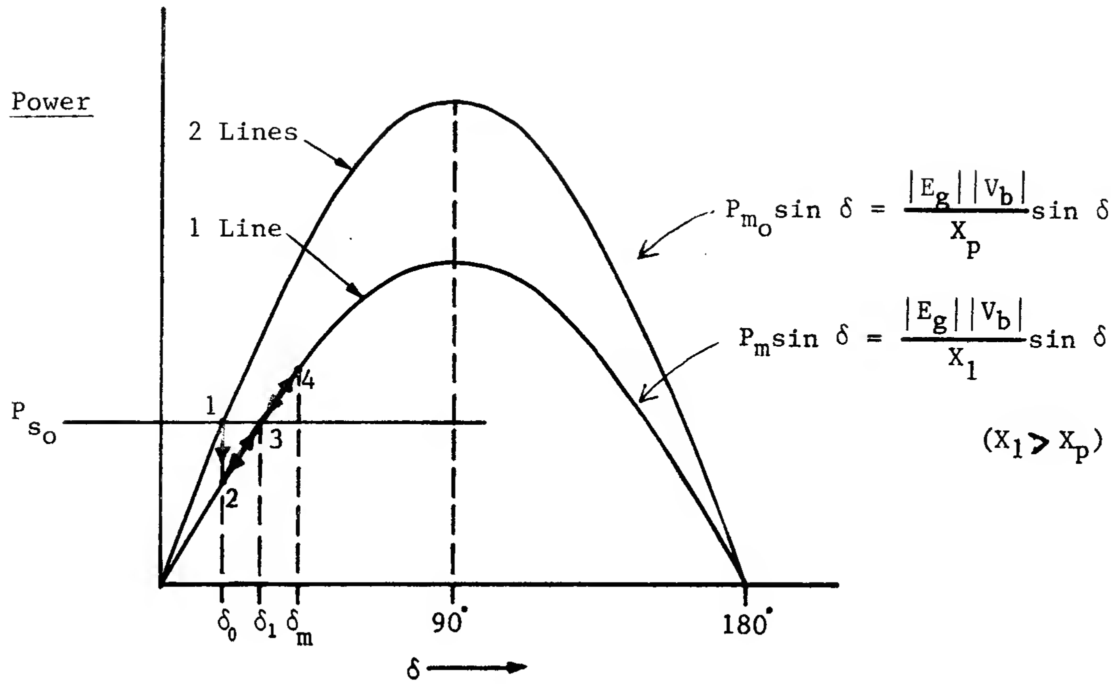
$$M\frac{d^2\delta}{dt^2} = P_{s_o} - P_m\cdot\delta \qquad (\delta_o = \frac{P_{s_o}}{P_{m_o}})$$

where $k^2I\omega_s = M =$ effective angular momentum.

Since the equation was made linear, the Laplace transform may be applied and we find that

$$\delta(t) = (\delta_o - \frac{P_{s_o}}{P_m})\cos\sqrt{\frac{P_m}{M}}t + \frac{P_{s_o}}{P_m}$$

This is a reasonable answer, considering all the approximations made, as can be seen graphically.



The above expression may be written (since $P_{s_o} = P_{m_o}\,\delta_o$)

$$\delta(t) = \delta_o\left[1 + \frac{X_1}{X_2}\left(1 - \cos\sqrt{\frac{P_m}{M}}\,t\right)\right]$$

At t = 0, the loss of line-2 drops the operating point to 2, when, since P_{s_o} is constant, the generator accelerates all the way to point 4, slows, and continues to oscillate about the new stable point 3. We should expect the

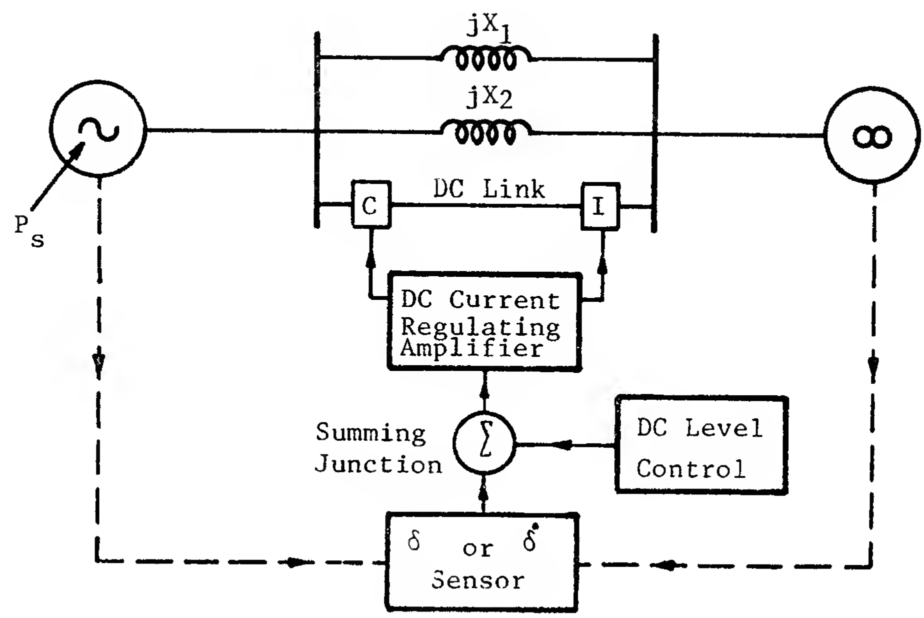
$$\cos\sqrt{\frac{P_m}{M}}\,t$$

term to decay away leaving the new final angle $\delta_1 = \delta_o\left(1 + \frac{X_1}{X_2}\right)$ larger than δ_o. (We should look, then, for an e^{-kt} term which can multiply the

$$\cos\sqrt{\frac{P_m}{M}}\,t$$

term in order to diminish it.)

CASE II: The system is in steady-state and suddenly line-2 is removed. Shaft input power stays constant at P_{s_o}. A DC-line parallels the AC lines and the DC power flow is $P_{dc} = P_{dco} + D\cdot(\delta \text{ or } \dot{\delta})$, i.e., a varying component, proportional to δ or $\dot{\delta}$, "rides on" the DC steady value.



The equation to solve is now

$$M\,\frac{d^2\delta}{dt^2} = P_{s_o} - P_m\,\delta - P_{Dc}$$

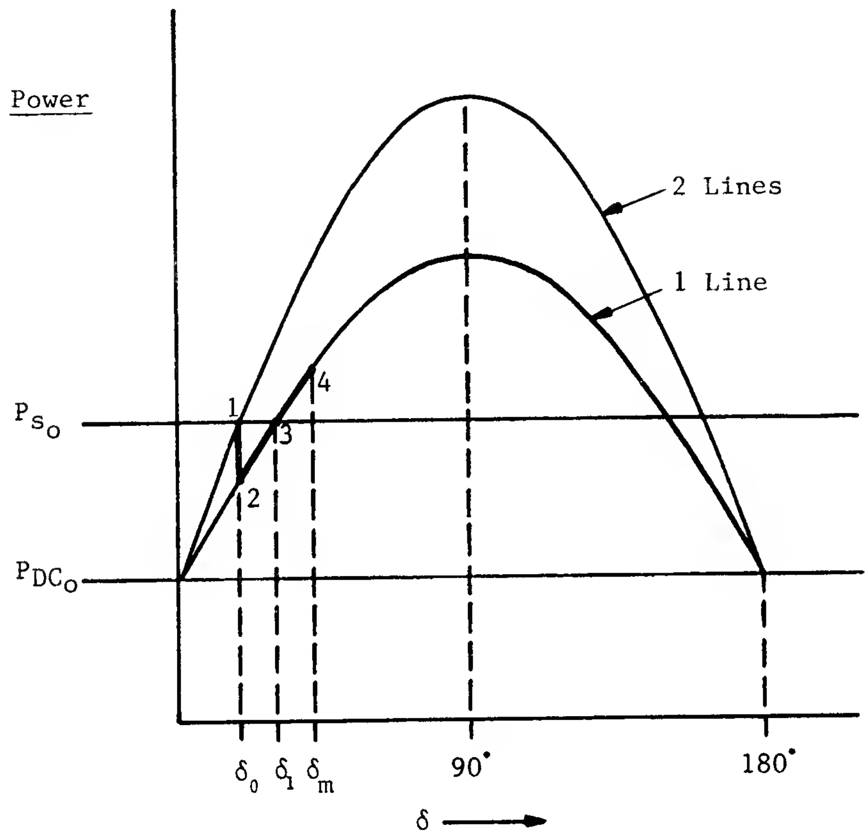
Now if $P_{Dc} = P_{Dco} + D\cdot\delta$, that is, if the control signal used is the angle δ (Θ- control in the case study), we have

$$M\,\ddot{\delta} = P_{s_o} - P_{Dc_o} - (P_m + D)\,\delta$$

Comparing with the previous solution, we have

$$\delta(t) = \left(\delta_o - \frac{P_{s_o} - P_{Dc_o}}{P_m + \delta}\right) \cos\sqrt{\frac{P_m + D}{M}}\,t + \frac{P_{s_o} - P_{Dc_o}}{P_m + D}$$

where $\delta_o = \frac{P_{s_o} - P_{Dc_o}}{P_{m_o} + D}$ and we can predict a smaller initial and final torque angle as well as smaller oscillation amplitude about the new torque angle. See below.



We see again, however, no readily evident decay of the oscillations (no e^{-kt} multiplier) so we conclude the situation may be improved, but not as much as desired. Again we have to depend on intuitive expectations to predict the desired settling down.

Suppose, however, we use $\frac{d\delta}{dt}$ (or $\frac{d\Theta}{dt}$ in the case study) control so that

$$P_{Dc} = P_{Dc_o} + D \cdot \dot{\delta}$$

and

$$M \ddot{\delta} = P_{s_o} - P_{Dc_o} - P_m \delta - D \dot{\delta}$$

Apply the Laplace transform again, with $\delta(o) = \delta_o$, $\dot{\delta}(o) = 0$, and

$$M \left[S^2 \Delta(S) - S\delta_o \right] = \frac{P_{s_o} - P_{Dc_o}}{S} - P_m \Delta(S)$$

$$- D \left[S\Delta(S) - \delta_o \right]$$

Divide both sides by M; collecting co-efficients of $\Delta(s)$ and completing the square gives

$$\Delta(s) \left[(s + \frac{D}{2M})^2 + (\frac{P_m}{M} - \frac{D^2}{4M^2}) \right] = \frac{P_{s_o} - P_{Dc_o}}{Ms}$$

$$+ \delta_o \; (S + \frac{D}{M})$$

Each term of the transform $\Delta(s)$ will therefore have

$$\left[(S + \frac{D}{2M})^2 + (\frac{P_m}{M} - \frac{D^2}{4M^2}) \right]$$

in the denominator and three cases arise

a. $\frac{P_m}{M} < \frac{D^2}{4M^2}$ (Over-damped case)

b. $\frac{P_m}{M} = \frac{D^2}{4M^2}$ (Critically-damped case)

c. $\frac{P_m}{M} > \frac{D^2}{4M^2}$ (Oscillatory case)

In case (a), exponentially-damped hyperbolic sines and co-sines appear, in (b) only exponential (negative exponent, of course) terms appear, and in (c) there are exponentially damped sines and cosines. In all cases, we clearly see that the generator will settle down on a new torque angle.

Examining the critical case $(\frac{P_m}{M} = \frac{D^2}{4M^2})$ further, we have (let $\frac{D}{2M} = a$)

$$\Delta(s) = \frac{P_{s_o} - P_{Dc_o}}{Ms}\left(\frac{1}{s+a}\right)^2 + \frac{\delta_o S}{(s+a)^2} + \frac{-2a\delta_o}{(s+a)^2}$$

The solution is

$$\delta(t) = \frac{P_{s_o} - P_{Dc_o}}{Ma^2}\left[1 - e^{-at}(1 + at)\right] + \delta_o e^{-at}(1 + at)$$

and since

$$P_m = Ma^2 = M \cdot \frac{D^2}{4M^2}$$

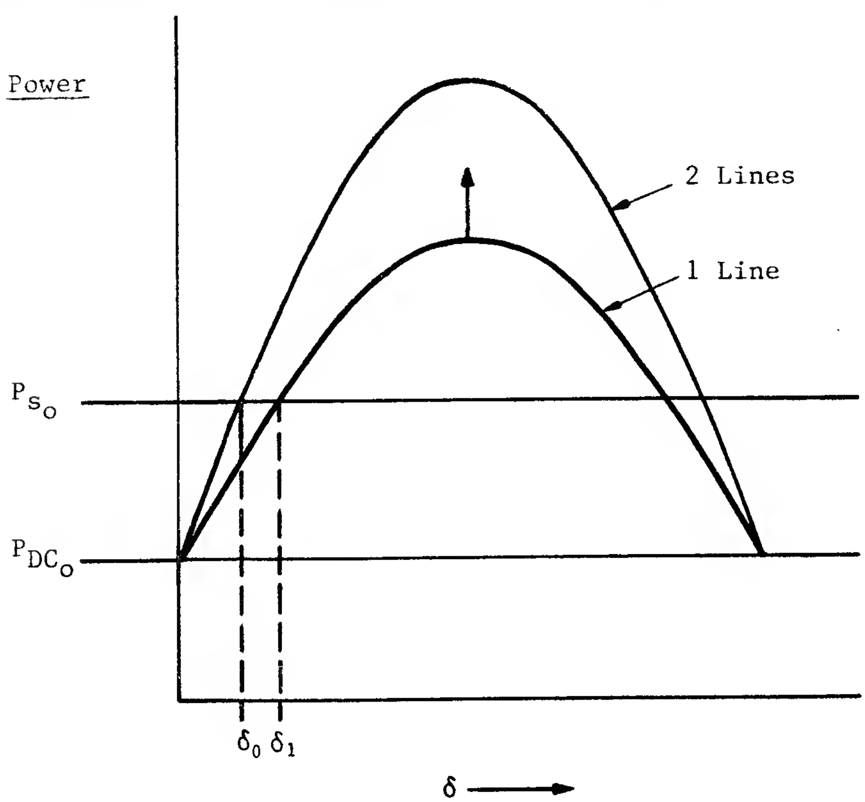
we have

$$\delta(t) = \frac{P_{s_o} - P_{Dc_o}}{P_m}\left[1 - e^{-\sqrt{\frac{P_m}{M}}\,t}\left(1 + \sqrt{\frac{P_m}{M}}\,t\right)\right] + \delta_o e^{-\sqrt{\frac{P_m}{M}}\,t}\left(1 + \sqrt{\frac{P_m}{M}}\,t\right)$$

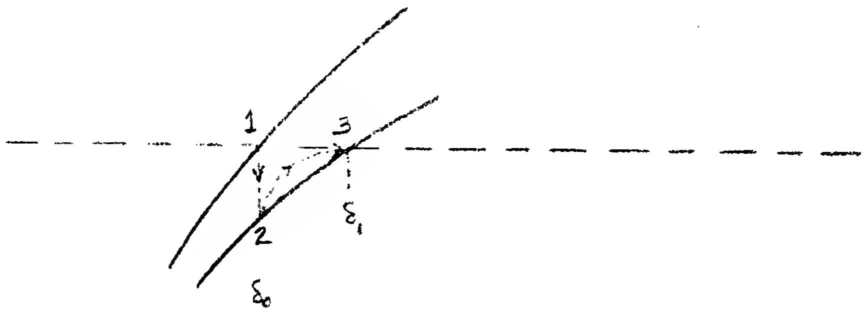
The final δ becomes $\frac{P_{s_o} - P_{Dc_o}}{P_m}$, as expected, and we find that the critical damping constant is

$$D_c = 2\sqrt{M \cdot P_m}$$

We could go back now and calculate the maximum rate of change of $\delta(t)$, multiply by D_c and find the maximum DC power required. A more complete treatment may be found in Reference 5 by Kirkham. Graphically, we see what happens.



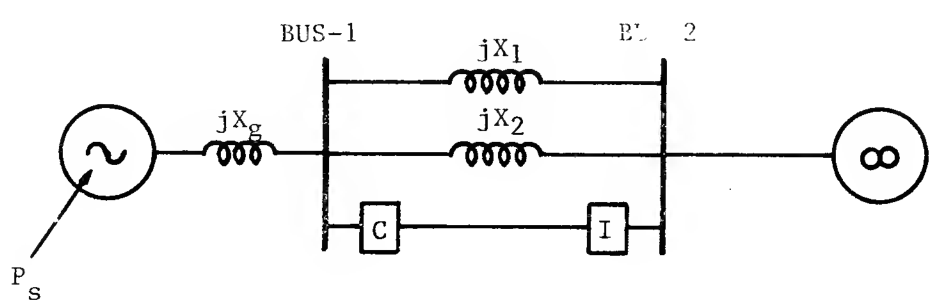
When line-2 is lost, the drop to the single line curve is accompanied by a simultaneous acceleration of the generator and a raising of the DC level. We can think of the 1-line curve as being lifted up and slowly brought back down until δ_1, the new power angle, is reached. An approximate path followed by point 1 would be as shown.



It must be emphasized again that the results depicted are only approximate since damper windings on the generator--which would only add still another term exactly like the $D\delta$ term used in the equation, generator reactance, all real power losses, and several non-linearities were ignored. Even so, the analysis is informative. Other variants of interest are to

1. Let P_m stay constant and allow P_s to increase or decrease. Observe what kind of pictorial representations results.

2. Consider the diagram below, with $\frac{d\Theta}{dt}$ control.



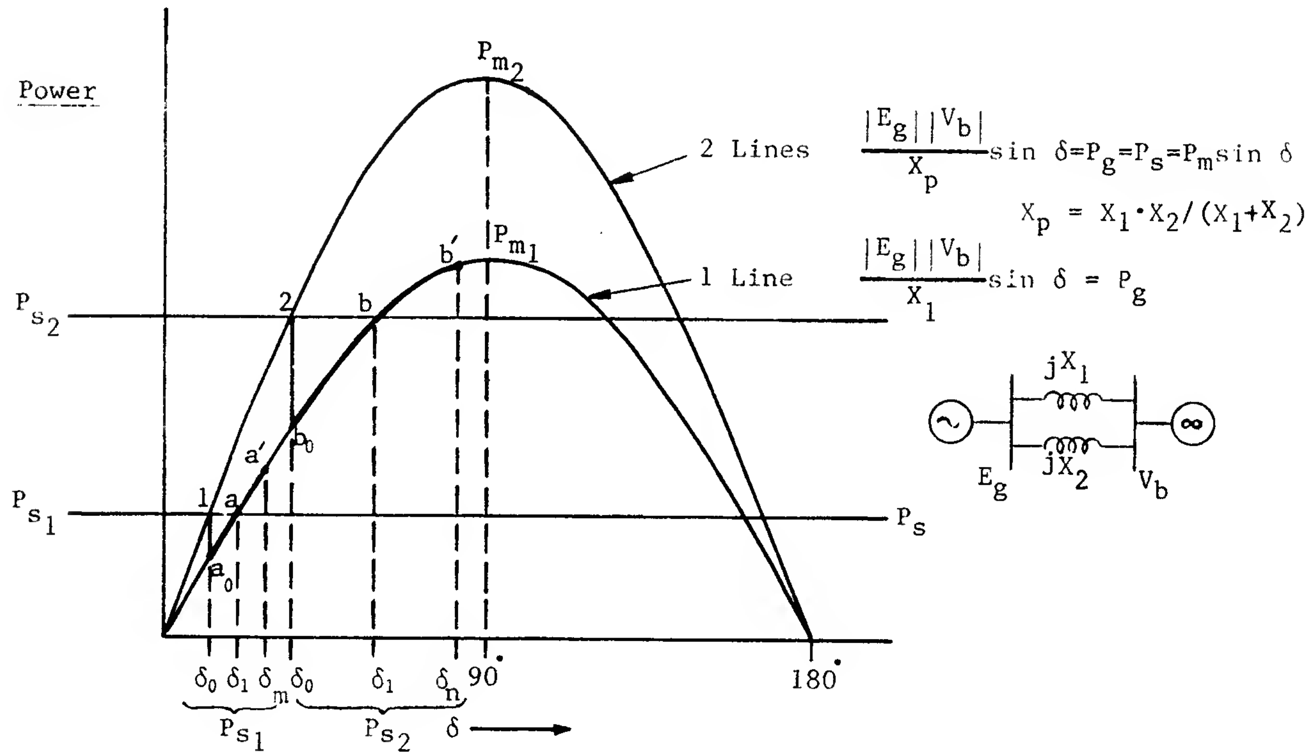
Here the machine reactance is included. One of RP56's engineers analyzed this system. (See Reference 5.)

3. Analyze the case when the total real power flow into the ∞-bus is kept constant even though line-2 is lost.

4. Write and examine results from a computer program of the non-linear case, using numerical values typical of lines and machines. RP56 staff engineers also worked on this problem.

SUPPLEMENT 2B

REAL POWER FLOW, TORQUE ANGLE, STEADY-STATE, AND TRANSIENT STABILITY



Section 2, Appendix B, showed how the curves above are obtained. Now, if the amount of real power to the ∞-bus transmitted over the lines is increased slowly by increasing the generator shaft input, the $\delta = 90°$ point could finally be reached.

This value of transmitted power, Pm, is termed the "Steady-State Stability Limit," since any further increase in shaft input power will cause a rapid increase in shaft

speed and the generator will run away with itself. Real mechanical power input is being still further increased while real electrical output is being decreased. The excess power must go into an accelerating rotor's kinetic energy.

From this consideration we see that shaft input Ps_1 is a safer operating point than Ps_2 since, if line-2 is lost, there is more likelihood that the transient swing in δ, $b_o \rightarrow b \rightarrow b'$ will go near the critical point $\delta = 90^o$.

The "Transient Stability Limit" is that point on the 2-line curve which corresponds to or would result in a maximum transient δ (primed points) on the 1-line curve equal to 90^o.

It is easy to see then that we could expect that the use of $d\delta/dt$ control raises the transient stability limit, meaning that the transmission link can be operated at higher ratings more safely than before, if stability is the only consideration. Of course, there is the possibility of losing the DC-line also. This contingency was investigated by the staff of RP56.

Thus, when line-2 is lost, the operation of the $d\Theta/dt$ control raises the base of the 1-line curve and there is less likelihood the transient swing in δ will reach 90^o.

BIBLIOGRAPHY

1. Stevenson, W. D. Elements of Power System Analysis. McGraw-Hill Co., N. Y. 1962. (esp. Chap. 15).

2. Elgerd, Olle I. Electric Energy Systems Theory: An Introduction. McGraw-Hill Co., N. Y., 1971. (esp. Chap. 12).

3. Dougherty, J. J. and T. Hillesland. "Power System Stability with Dynamically Responsive DC Transmission Lines," I.E.E.E. Paper No. 69 TP 37-PWR, presented at the I.E.E.E. Winter Power Meeting, 1969.

4. Dougherty, J. J. and H. Kirkham. "System Aspects of a Tapped DC Line with Dynamic Controls," I.E.E.E. Transactions On Power Apparatus and Systems, Vol. PAS-89, No. 8, Nov-Dec, 1970.

5. Kirkham, H. "Fundamental Considerations of Power System Stability with Dynamically Responsive DC Transmission Lines," EEI Report No. S-107, December, 1969.

INSTRUCTOR'S GUIDE

CASE TITLE: Research on AC/DC Electric Power Systems and System Stability Techniques

RELATED UNDERGRADUATE CURRICULUM AREAS:

1. Engineering analysis and design methods.

2. Control Theory.

3. Active filter theory (a low-frequency application).

4. Power systems analysis (AC/DC systems).

SYNOPSIS: An electrical engineer working in the research division at the Philadelphia Electric Company became manager of a project whose objective was to study the operation of high power direct-current transmission lines working in parallel with the usual AC lines. Such hybrid power systems were in operation in Europe and the USSR and were being planned in the U. S.; a number of electric companies had decided, therefore, to support a new research project organized through the Edison Electric Institute. The engineer, having become manager of the research project through an interesting series of circumstances, reported to a supervisory committee with members from the power companies and EEI.

The decision was made to build a small but realistic model of a power system with both AC and DC sub-systems. Once this physical model was built, a long series of tests ensued and showed that one important feature of such an arrangement was the improvement of over-all system stability, undesirable disturbances being more quickly damped out. Damping action was controlled by varying the amount of DC power transfer in accord with the change of power angle between two busses. A better control signal was found to be the time rate of change of that power angle. The control circuitry to respond to that derivative signal was therefore designed and tested. A theoretical discussion of the "swing equation" and its mathematical treatment is included in the appendix to aid understanding of the damping action.

This case shows how, over an extended period of time, the project manager coordinated efforts of a number of engineers from the various power companies and performed other duties of a technical manager. It also shows how an electronic circuit evolves as its design is progressively improved upon.

QUESTIONS FOR THOUGHT AND DISCUSSION:

After reading Part A:

1. What are advantages and disadvantages of overhead DC transmission lines and AC transmission lines? Underground lines?

2. Why was the research project considered especially important by the electric utilities?

3. Explain the concept of a steady-state stability limit (see Supplement 2B). Transient stability limit.

4. What part did communication skills play in John Dougherty's work as project manager? Would he have been chosen for the job if such skills were absent?

5. What part did a literature search play in the first period of the project?

After reading Part B:

1. How was it first observed that system disturbances could be damped quickly by varying the DC power flow?

2. Describe the design steps which led finally to the $\frac{d\Theta}{dt}$ control circuitry. Can further improvements be suggested?

3. Clearly analyze the operation of the differentiator and limit control circuitry in the $\frac{d\Theta}{dt}$ circuit.

4. Important test results are shown in Exhibit 1B. Clearly explain these curves. Do they show positively the damping action claimed in the project report?

5. How may this AC/DC research project's final conclusions be related to the present "energy crisis" in the U. S.?